STRATIGRAPHY, SEDIMENTOLOGY AND HYDROCARBON PROSPECTS OF THE DILWYN FORMATION IN THE CENTRAL OTWAY BASIN OF SOUTH EASTERN AUSTRALIA

By G. R. Holdgate

State Electricity Commission of Victoria

Abstract: A sedimentary and facies analysis from deep bore data in the central Otway Basin indicates the Early Eocene Dilwyn Formation comprises up to seven stacked deltaic cycles. The oldest, Delta Cycle A, derived much of its sediment from two main fluvial fed sources coming from north of the basin, and possibly north of the present divide. The fluvial sequences coalesced south of a hinge line at the Tartwaup Fault, and filled the deep northwest-southeast trending Portland Trough. This delta cycle comprises the prodelta sequences of the Pember Mudstone Member, grading up into two main high constructive elongate delta channels similar to those of the present day Mississippi birdfoot. Subsequent Deltas B to G are high sand-shale ratio cycles elongate parallel to the Portland Trough margins. Each cycle begins with marine shales. Size analysis and isopachs of sand suggest the constituent sand bodies of each cycle include barrier bars and delta front channels. Fluvial channel sands dominate in the upper parts of the cycles and towards the north of the basin. Each cycle was terminated abruptly by renewed marine transgression. The cycling is best explained by channel switching and abandonment of sediment supply, than by the eustacy model. Extrapolation into offshore areas of the basin indicates some hydrocarbon potential exists in the more deeply buried sands of the prodelta sequences, and an explanation for the submarine canyons on the continental slope is proposed.

INTRODUCTION AND METHODS

In the Otway Basin of south-eastern Australia Palaeocene to Middle Eocene sediments are referred to as the Wangerrip Group, including a basal Pebble Point Formation conformably overlain by the Dilwyn Formation which comprises the major portion of the Wangerrip Group. This study concentrates on the subsurface central part of the Basin between the Victoria-South Australia border and the Warrnambool Ridge (Fig. 1) which encompasses the two major onshore Gambier and Tyrendarra Embayments. Most sedimentological work was carried out on the former embayment, using 16 deep groundwater and stratigraphic exploration bores drilled by the Department of Minerals and Energy, Victoria (DMEV). Cuttings samples were examined every 3 m, as well as core samples cut approximately every 100 m, and wire line geophysical logs including gamma ray, spontaneous potential (SP) and resistivity. Similar data from other bores drilled for oil and water in the area and interpretation based on geophysical logs for most deep DMEV bores in the Tyrendarra Embayment have completed the programme. Examination of the extensive oil company seismic data coverage of this area has not been attempted in this study.

The Dilwyn Formation was first described by Baker (1943, 1950) from coastal cliffs near Princetown and later named the Dilwyn Clay (Baker 1953). Bock and Glenie (1965) introduced the name Dilwyn Formation with a lower Pember Mudstone Member and an upper Dartmoor Sand Member, to describe the subsurface sediments. In the western Otway Basin near the Glenelg River Boutakoff and Sprigg (1953) named similar strata as the Dartmoor Formation, now regarded as a junior synonym of the Dilwyn Formation (Abele *et al.* 1976). In South Australia this formation is known as the Knight Group (Ludbrook 1971). For convenience both the outcrop and subsurface occurrences are referred to as the Dilwyn Formation.

The Dilwyn Formation in the subsurface has been referred to only in general terms in well completion reports and basin summaries, and the more detailed descriptions of Abele *et al.* (1976), apply mainly to the sparse outcrops. Its depositional environment has been considered to be paralic (Bock & Glenie, 1965). This study examines the information available from bores, and makes an assessment of the depositional environments from these data using techniques developed by oil companies for similar paralic environments. The conclusions reached probably apply to the Dilwyn Formation throughout the Otway Basin.

RESULTS

Subdivisions

In the study area the Dilwyn Formation can be subdivided into three parts described below, the characteristic wire line logs of which are shown on Figs 5 & 6.

1—The Pember Mudstone Member is the oldest unit and consists of tan to grey siltstones, mudstones and shales, usually pyritic, carbonaceous, micaceous and locally glauconitic. Carbonate cemented sands are common particularly in the upper parts. Owing to later uplift and erosion many of the basin margin outcrops occur within this unit.

2—The undifferentiated Dilwyn Formation is the thickest unit generally comprising two-thirds of the total formation. It is characterised by sands predominating over shales, and cyclic repetitions of sands-silts-clays. This unit includes the Dartmoor Sand Member of Bock and Glenie (1965) which cannot be distinguished in this

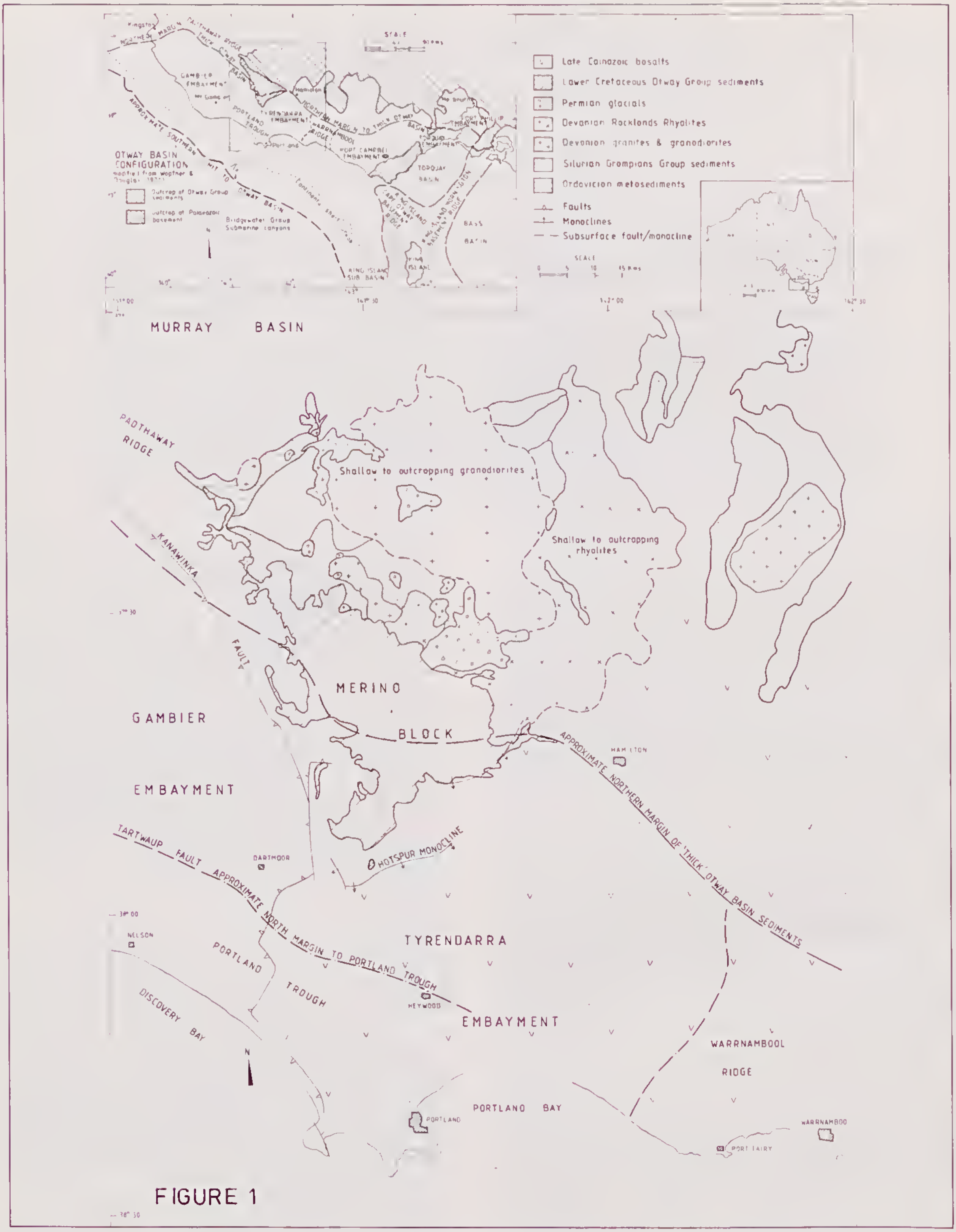

Fig. 1—Central Otway Basin general geology. (From Portland 1:250 000 Geological Sheet)

central area of the Otway Basin. It is transitional with the Pember Mudstone Member below. When the overlying Burrungule Member is absent the Dilwyn Formation appears on bore hole sections (Fig. 6) to be unconformable with overlying carbonate units such as the Gambier Limestone.

3—The Burrungule Member is mainly recognized south of the Tartwaup Fault. However, thin non-marine coaly equivalents may be present for a short distance to the north of the fault. It includes all the well burrowed grey muddy siltstones with lesser sands which conformably overlie the undifferentiated Dilwyn Formation and underlie the Mepunga Formation and other marine carbonate deposits. Not uncommonly it includes a calcareous marine fauna of foraminifera and shelly fossils. It has not been described from the Otway Basin Victoria before, but is in the South Australian portion (Harris 1966).

Recognition in the Subsurface

The Dilwyn Formation occurs in all bores throughout the study area except where removed by subsequent erosion. It underlies younger marine carbonate units such as the Mepunga Formation, Gambier Limestone and Heytesbury Group, or the Whaler's Bluff and Bridgewater Formations. North of the Tartwaup Fault these overlying carbonate sequences truncate the beds of the Dilwyn Formation. It overlies conformably the Pebble Point Formation or unconformably the Otway Group in the far north.

The Dilwyn Formation sands are readily distinguishable from those of the Mepunga Formation and Pebble Point Formation by their lack of brown oxidation and better sorting and roundness. Upper Cretaceous Paaratte Formation sands are similar to Dilwyn sands but, in all cases, the Pebble Point Formation intervenes (Holdgate 1977c). Bores in the far NW lack the Pebble Point Formation but here the Dilwyn rests unconformably on Early Cretaceous Otway Group. Tertiary uplift on basin margins and structural highs has caused truncation of the Dilwyn Formation. In some bores complete removal has occurred, e.g. Myaring 2 where Pleistocene Whaler's Bluff Formation rests unconformably on Pebble Point Formation.

Description of Lithologies

Sands—typically well sorted and clean, with clear frosted well rounded quartz grains of mean size 1.0 phi in the south to 0.4 phi in the north. More detailed sand size analyses are made in subsequent sections. The sands occur in sand bodies which range from 15 m to 30 m in thickness but can exceed 80 m locally. Some sand bodies coarsen upwards but others remain constant in grain size throughout. The lower contacts can be gradational with underlying muddy sands and silts, or abrupt with clays and shales. The upper contacts are generally abrupt and overlain by ligneous clays and silts. The sand bodies comprise over half of the formation thickness but average less than one quarter of the thickness in the Pember Mudstone and Burrungule Members. Core recoveries are low in the sands but improve with depth. They often fall below 20% due to the overall lack of consolidation. On wire line logs they commonly show short normal resistivities of 20 ohms/m². The cemented sands can be up to 30 or 40 ohms/m². Most sands are fresh water flushed and on pumping can produce water flows up to 125 litres/second (Lawrence 1976). Water quality is good with low salinities. Calculations using neutron and density logs in Warrain 7 bore show porosities to decrease from 50% at 665 m to 28% at 1350 m (Laing in Holdgate 1977a).

Shales—usually tan to grey, and laminated by fine white silty interbeds. In the lower part of the Pember Mudstone the shales become massive without obvious bedding, and here can be over 100 m thick. Dark grey and black shales occur near the base of the formation in the deep parts of the basin. Gamma ray logs show the shales range between 0.015 and 0.02 mr°/hr. Maximum intensities mainly occur in shales of the Pember Mudstone, and the lower shales in the cyclic sequences.

Silts are most common in the Burrungule Member. The mottling and burrowed appearance of these silts is due to infillings of animal burrows by cleaner white silts. This lithology is also present in the rest of the formation particularly in the lower shales of the cyclic sequences.

Cemented sandstones are common in the upper parts of the Pember Mudstone and as occasional interbeds in the undifferentiated Dilwyn Formation near the base of the cyclic sequences. On the resistivity logs they have a spike-like appearance. From their stratigraphic position it can be inferred that the carbonate cementing media may be of a primary origin. Chemically, they range between dolomite, siderite, silica and pyrite.

Calcareous fossils are rare except in the Burrungule Member. Planktonic foraminifera have been obtained from this and the Pember Mudstone and more rarely from the lower shales in the undifferentiated part. Siliceous foraminifera including species of *Cyclammina* are more common throughout the formation occurring mainly in the shales. Sharks teeth can also be found.

Carbonaceous material is present in both sands and shales as disseminations and discrete beds (stringers). Thin coal seams up to a few metres thick occur in the upper parts of the cyclic sequences and in the Burrungule Member. Their poor definition from the gamma ray logs suggests they contain high ash contents.

Mica is common throughout the formation with large flakes lying parallel to bedding. In the Nelson Bore the heavy mineral fractions seldom exceed 0.5% by weight (Baker 1961), and most of this is authigenic pyrite and heavy carbonates. From Baker's table of percentage distribution (Baker 1961, Table 13), the non-authigenic minerals in the Dilwyn formation comprise about 50% zircon with the rest evenly separated between tourmaline, rutile, garnet, cassiterite and minor metamorphic minerals. This mature population distribution indicates extensive or long transport histories from a granite terrain. There appears to be no major change in the heavy mineral population throughout the Dilwyn Formation.

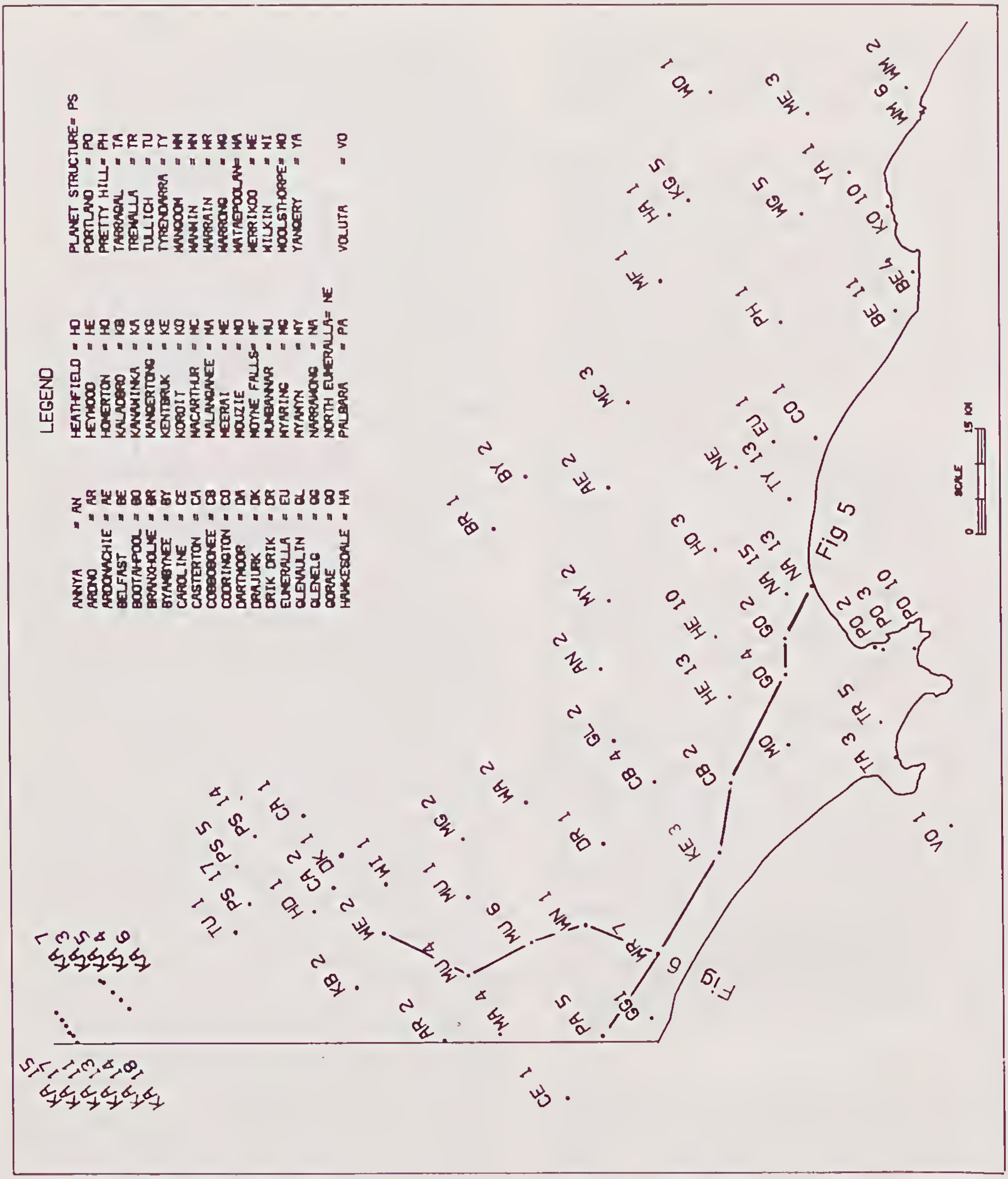

Fig. 2—Central Otway Basin bore location plan.

Distribution and Thickness

The formation ranges in thickness between 6.1 m in the north-west to greater than 1247 m in the south-east, and occurs in the subsurface throughout the study area. The isopach map (Fig. 3) shows the general distribution of sediments. Thicknesses over 600 m are limited to that part of the study area south of the Tartwaup Fault where a deep trough is developed. The depocentre for this trough occurs in the Tyrendarra Embayment. North of the Tartwaup Fault the isopach lines strike north-west parallel to and deepening south-west away from the Kanawinka Fault.

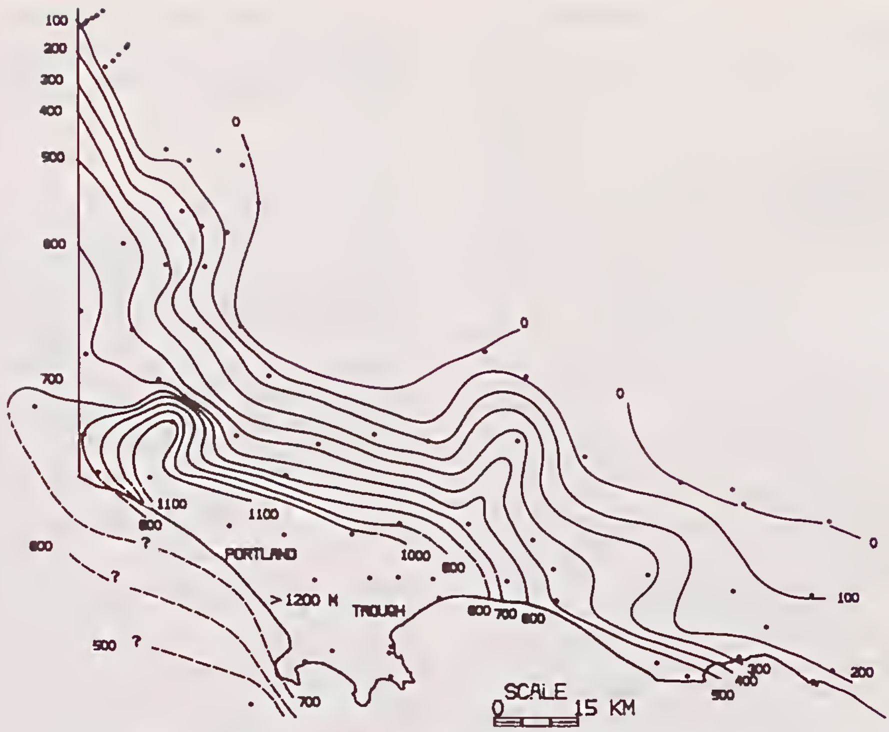

Fig. 3—Central Otway Basin isopach of Dilwyn Formation (metres).

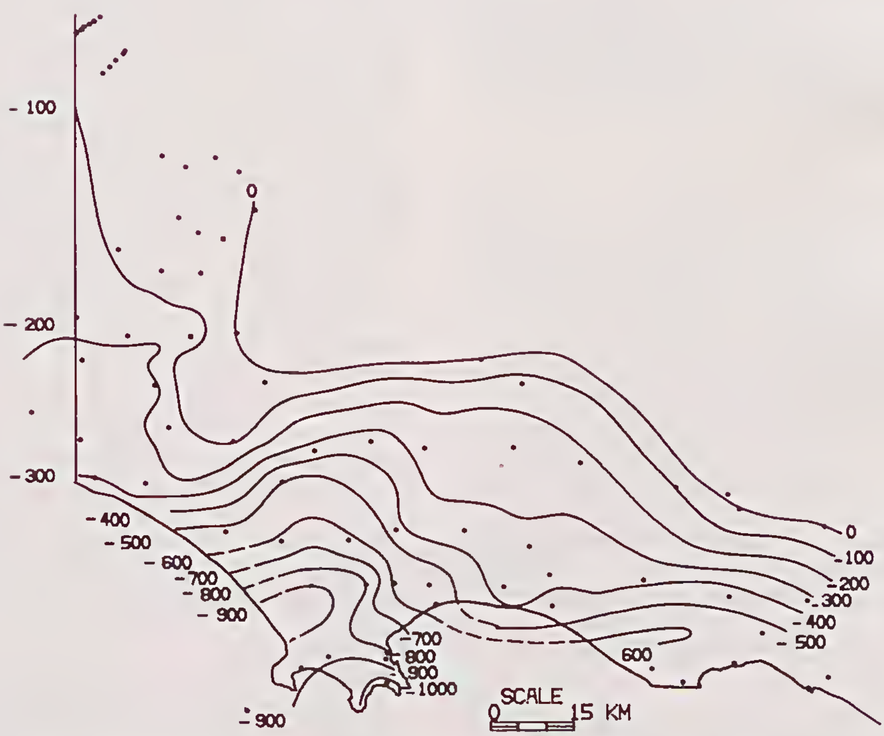

Fig. 4—Central Otway Basin structure contours to top of Dilwyn Formation (metres).

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The structure contour lines on top of the Dilwyn Formation (Fig. 4) indicate a structural high around Dartmoor plunging south-west towards Nelson township, part of which has been referred to as the Stokes River Anticline (Kenley 1971). To the north of this anticline the structure lines indicate progressive deepening away from the Kanawinka Fault towards the State border. To the south there is rapid deepening into the Tyrendarra Embayment. The Dartmoor Ridge of Boutakoff (1952), which as a gravity defined structure was postulated to divide the Gambier and Tyrendarra Embayments, is not in evidence in the subsurface and has little effect on the early Tertiary formation. Portland Trough is herein proposed to describe the thick east-west Tertiary sequence which straddles this 'ridge'.

The Portland Trough commences shortly east of Nelson township as indicated by the isopach lines around Wanwin 1 and Warrain 7 bores, and deepens and broadens to the south-east in the general direction of Portland. To the north it is limited by the rapid shallowing of section along the line of the Tartwaup Fault, to the west by structural shallowing in the Nelson-Caroline area, and opens to the south and south-east into Portland Bay. All the DMEV bores in the centre of the trough failed to penetrate the full sequence, which probably exceeds 2000 m. The only offshore well south of Portland (Shell Dev. Voluta No 1) drilled a thinner sequence of Dilwyn Formation, which is taken here as indicating that a southern margin to this trough occurs offshore in Discovery Bay.

The trough has two north trending re-entrants which have important palaeoenvironment implications discussed later. One occurs on the north-western edge of the trough around the Wanwin 1 and Mumbannar 6 bore sites, and a larger re-entrant occurs in the Tyrendarra Embayment trending north towards the Hamilton area.

Age

In the subsurface, the Dilwyn Formation generally ranges from Middle Palaeocene to Middle Eocene in age (Abele *et al.* 1976) although McGowran (1978) considers the time interval between Late Early Eocene and Early Middle Eocene may be absent. In the study area it includes the *L. balmei* and *M. diversus* spore-pollen zones of Stover and Partridge (1973) (see Ripper 1976). The *T. collactea* (Late Middle Eocene) foraminiferal zone of McGowran (1973) occurs in the Burrungule Member.

The Pember Mudstone contains planktonic foraminifera of Palaeocene to Early Eocene age which have been identified in core material from Malanganee 4 (835.5 m) by Abele in Holdgate (1977b) and Wanwin 1 (1215 m) by Abele in Holdgate (1975). Further identifications by Dr C. Abele (pers. comm.) include Ardonachie 2 (680 m), Gorae 2 (1369 m), Heywood 13 (1595.5 m), Mumbannar 1 (456 m) and Narrawong 15 (1552.8 m and 1675 m).

The undifferentiated Dilwyn Formation contains sparser foraminifera of Palaeocene to Early Eocene age including Cobboboonee 2 (1368.5 m) and Heywood 13 (900 m) (Dr C. Abele pers. comm.).

The Burrungule Member contains a planktonic foraminiferal fauna of late Middle Eocene age, in Warrain 7 (256 m and 272 m), Abele in Holdgate (1977a) and possibly Wanwin 1 (170 m), (Abele in Holdgate 1975).

Cyclic Sedimentation in the Undifferentiated Dilwyn Formation

From an examination of the wire line logs there occur characteristic gamma ray and resistivity log traces through the undifferentiated Dilwyn Formation which show cyclic repetition. These can be compared with similar cyclic gamma and electric log profiles considered to represent subsurface deltaic sequences (Galloway 1968, Fisher 1969, Weber 1971, Selley 1976). The principle used to determine the depositional environments from logs is related to the fact that gamma ray and electric log profiles reflect clay content in clastic sequences. From this the vertical changes in environment can be interpreted as well as lateral facies changes.

The correlation between vertical log profiles in a deltaic sequence and grain size obtained from side wall coring has been demonstrated by Weber (1971). To interpret Dilwyn Formation environments without the aid of sidewall cores, grain size analyses of cuttings samples were made on three bores. Cuttings samples every 3 m were washed free of drilling mud and sieved. The verticle distribution of grain sizes plotting relative distribution of the whole phi intervals in a cumulative plot coarsening from right to left is illustrated on Fig. 7 for the three bores. Cutting samples are not ideal for determining size distribution, but the correspondence between the wire line logs and size distributions is close, confirming that the cyclic sequences on the logs relate to similar cycles in the grain size. Each cycle commences with a sudden change from a sand in the preceding cycle to a shale or silty shale immediately above. In some bores this contact is associated with carbonate cemented sands and these along with calcareous planktonic foraminifera indicate the shales are of marine origin. The shales gradually decrease upwards to be replaced by two thick massive unfossiliferous sand beds at the top of the cycle, separated by a second thinner shaly interval. Grain sizes increase upwards through the transitional shaly silt and silty sand intervals but mean sizes stabilise through the massive sands.

Up to seven cycles can be recognized in each bore which can be readily correlated on logs throughout the study area and into the adjacent Tyrendarra Embayment (Figs 5 & 6). From the cuttings size analyses each cycle has a repeatable grain size distribution to the one below which is characteristic to each bore. Adjacent bores have similar vertical repeatability but different size distributions. Mean grain size appears to decrease away from the basin margins. North of the Tartwaup Fault the upper cycles are eroded from the structural highs and basin margins, so that progressively older cycles subcrop below the younger carbonate sequences. Individual cycles average 80 m in thickness but decrease towards the basin margins where there was a continuous positive influence. Basinwards there is an increase in

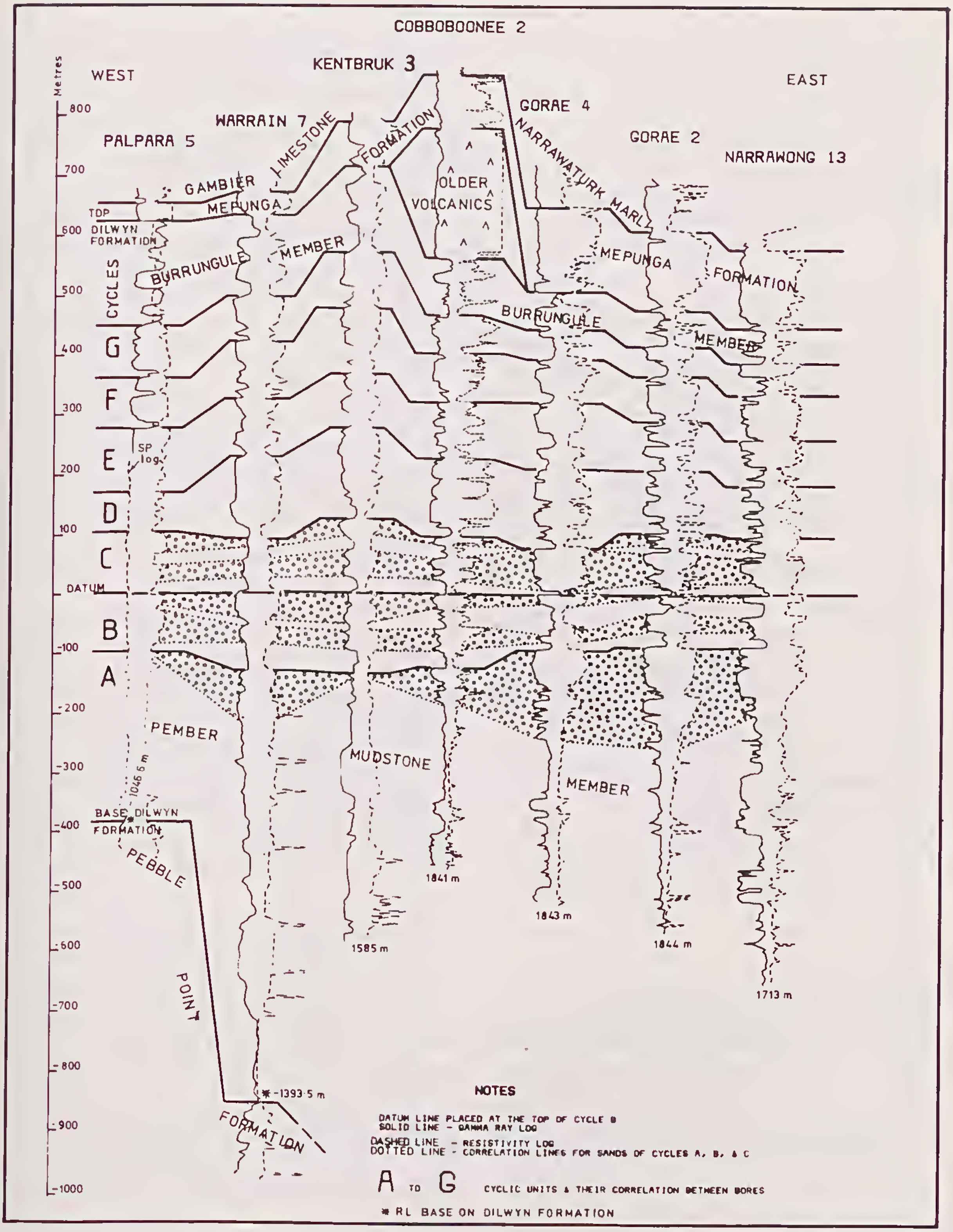

Fig. 5—Central Otway Basin Dilwyn Formation. East west log cross-section and reduced wireline logs.

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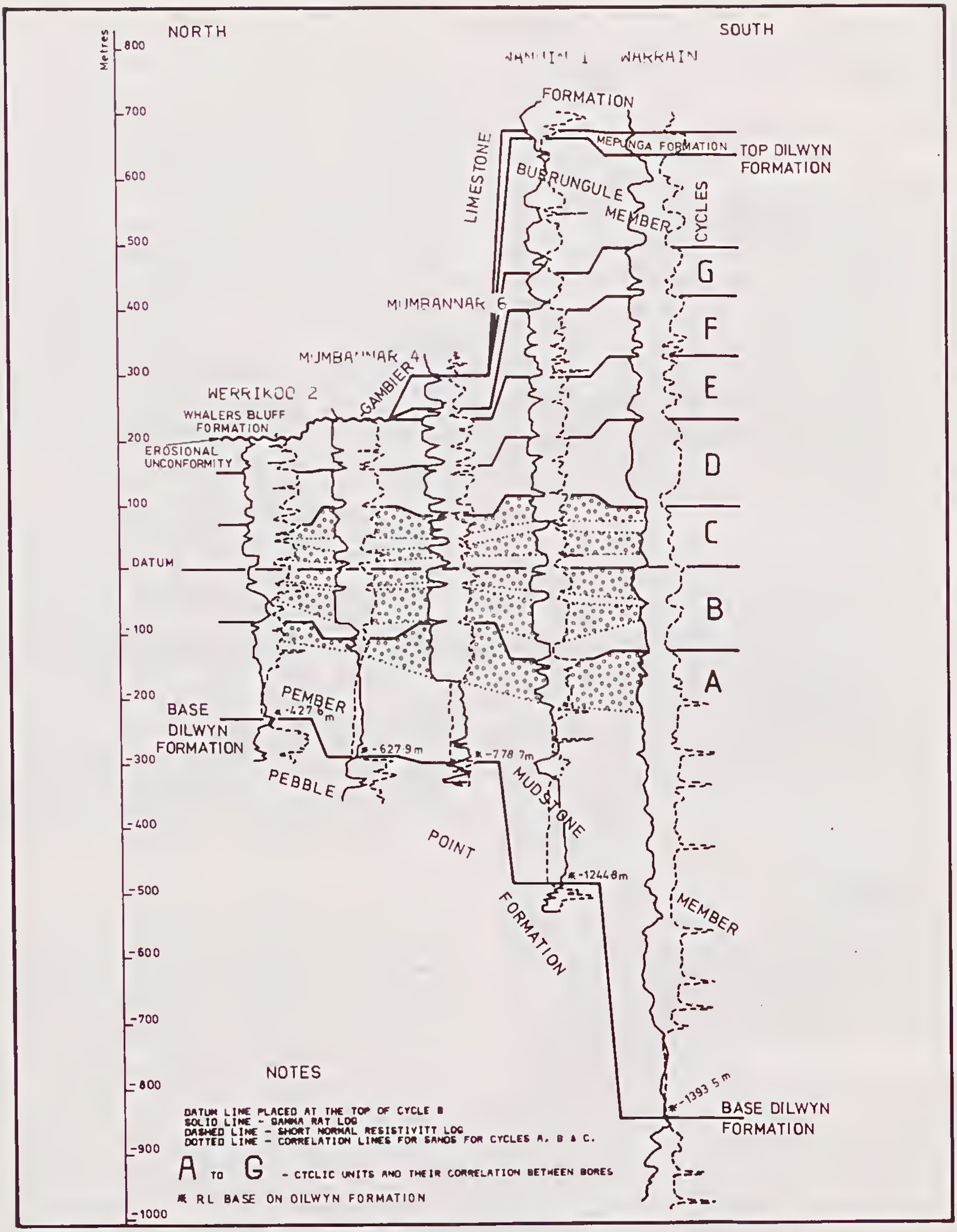


Fig. 6—Central Otway Basin Dilwyn Formation. North-south cross-section and reduced wireline logs.

shale as the proportion of sand decreases, and the major contributing factor to the thickening in the Portland Trough is the large increase in thickness of the Pember Mudstone and Burrungule Members.

The seven cycles are listed A to G in stratigraphic order. Cycles B to G characteristically have two sands and two shales. The lowest shale in each cycle has the higher gamma ray count, and can be fossiliferous and bioturbated. The lower sand in each cycle often shows a coarsening upwards sequence as indicated by grain sizes, and a gradually decreasing gamma log. In some bores the lower sand has a box-like log character produced by sharp contacts. These sand bodies are generally thicker than adjacent sands with transitional contacts. The upper sand bodies are usually box-like with sharp contacts. The lateral correlations between sand bodies for cycles A to C are shown on the bore log in Figs 5 and 6.

Cycle A differs from the other cycles whereby it can grade laterally from a single 90 m thick box-like sand body (Mumbannar 6) to a 15 m thick coarsening-up carbonate cemented sand body (Malanganee 4) (Fig. 8). Sizing the cuttings from the Mumbannar 6 bore indicates coarser sands occur in the upper and lower regions of the sand body, with little variation in grain sizes dominated by the 1 to 2 phi class range through the middle. On the bore log cross section through the Tyrendarra Embayment (Fig. 9), Cycle A consists of a series of three or more stacked box-like sand bodies, each up to 100 m thick. The relationships between vertical grain size profiles and wire-line log profiles conform to those deduced by Weber (1971) for fluvial distributary channels and barrier sands in the subsurface Niger Delta, although it should be noted that the Dilwyn sand bodies can have up to twice the thickness of the Niger Delta sand bodies.

Geometry of the Cyclic Units

Subsurface geometry of the individual cycles is depicted by a series of isopachs of each cycle (Figs 10 to 13). The Tyrendarra Embayment contains similar correlatable cycles which are included on the isopachs. Each cycle comprises a number of facies and environments, which in the sense of Busch (1971) make up an increment of sedimentation. The sum of all increments constitutes a genetic sequence of strata—in this case the undifferentiated Dilwyn Formation. It is envisaged that time-stratigraphic lines would transgress across the cycles but retain some conformity to the cycle boundaries.

Figures 11 to 13 show that for the most widespread Cycles B to D the major depocentres are coincident with the Portland Trough. The sand percentages for each cycle as derived from the gamma ray log indicate the basin margin areas are generally sandier. When considering the isopach for Cycle A (Fig. 10) some differences are apparent. This cycle has two depocentres—one in the Mumbannar/Warrain area, and one in the Gorae/Portland area. These trend at right angles across the main trough axis and contain the highest sand percentage. They are coincident with and extend southward from the re-entrants described previously at each end of the Portland Trough. Figures 8 and 9 show two bore hole log cross sections at right angles to these trends with the datum horizon placed on top of Cycle A. The channel-like nature of the sands is clearly visible, as are the lateral facies changes in these channels to the shales and carbonate cemented sands of the upper part of the Pember Mudstone.

Geometry of the Constituent Sand Bodies

Isopachs of each sand in Cycles A, B and C are shown on Figs 15 to 19, which depicts subsurface geometry of these sand bodies. Sand bodies for Cycles D to G are not shown due to partial erosion and correlation difficulties. The following points are noted:

1. The isopach of Cycle A sand body is the same as the isopach for the whole of Cycle A comprising two main depocentres opening to the south in the Mumbannar and Gorae areas. These have thicknesses over 60 m and are separated by an intervening low sand area in the Glenaulin and Kentbruck area (Fig. 15).
2. The isopach of the lower sand in Cycle B (Fig. 16) includes two parts—a SW trending depocentre with thicknesses over 60 m in the Mumbannar/Caroline area, connecting to an eastward trending depocentre through the Glenaulin, Heywood and Narrawong bores. Areas of minor sand thickness surround this sand body to the north, south and west.
3. The upper sand in Cycle B (Fig. 17) comprises a V-shaped depocentre through the middle of the study area with thicknesses exceeding 30 m. This forms a seaward perimeter to a low sand area in the north central area. A separate more localised trough occurs in the Tyrendarra bores.
4. The lower sand in Cycle C (Fig. 18) comprises a long narrow linear depocentre parallel to the Portland Trough axis, with thicknesses increasing south-eastwards to 60 m in the Gorae area. It is flanked to the north and south by low sand areas.
5. The upper sand in Cycle C (Fig. 19) comprises two depocentres; one in the Wanwin/Ardno area which opens into South Australia, and the other in the Tyrendarra area. These are separated by a low to absent sand zone through the Heywood/Cobboboonee areas.
6. An isopach of the main correlatable sand body which occurs in the middle of the Pember Mudstone is included for comparison (Fig. 14). It is a narrow linear shaped body with somewhat sinuous outline approximating in position to the Portland Trough. At its centre around Kentbruck it exceeds 60 m in thickness.

Dipmeter Analysis

As an additional aid to subsurface facies analysis dipmeter logs were available to derive sedimentary dips such as crossbedding, the directions of which may be used to indicate direction of source and directions of flow in channel sands. Outlines of the techniques for examining dipmeter logs for such features are described by Schlumberger (1970). Using the methods described, sedimentary dips are divided into two main categories—those where two or more sequential dips of similar directions increase in dip downhole (red patterns), and those which decrease in dip downhole (blue patterns). Ideally for sedimentary dips in channels red patterns indicate downdip thickening towards the channel axis, the blue patterns indicate direction of fill. For beach barriers and offshore bars dip direction may occur in either direction normal to the shoreline depending on whether the sediment was derived from the landward or

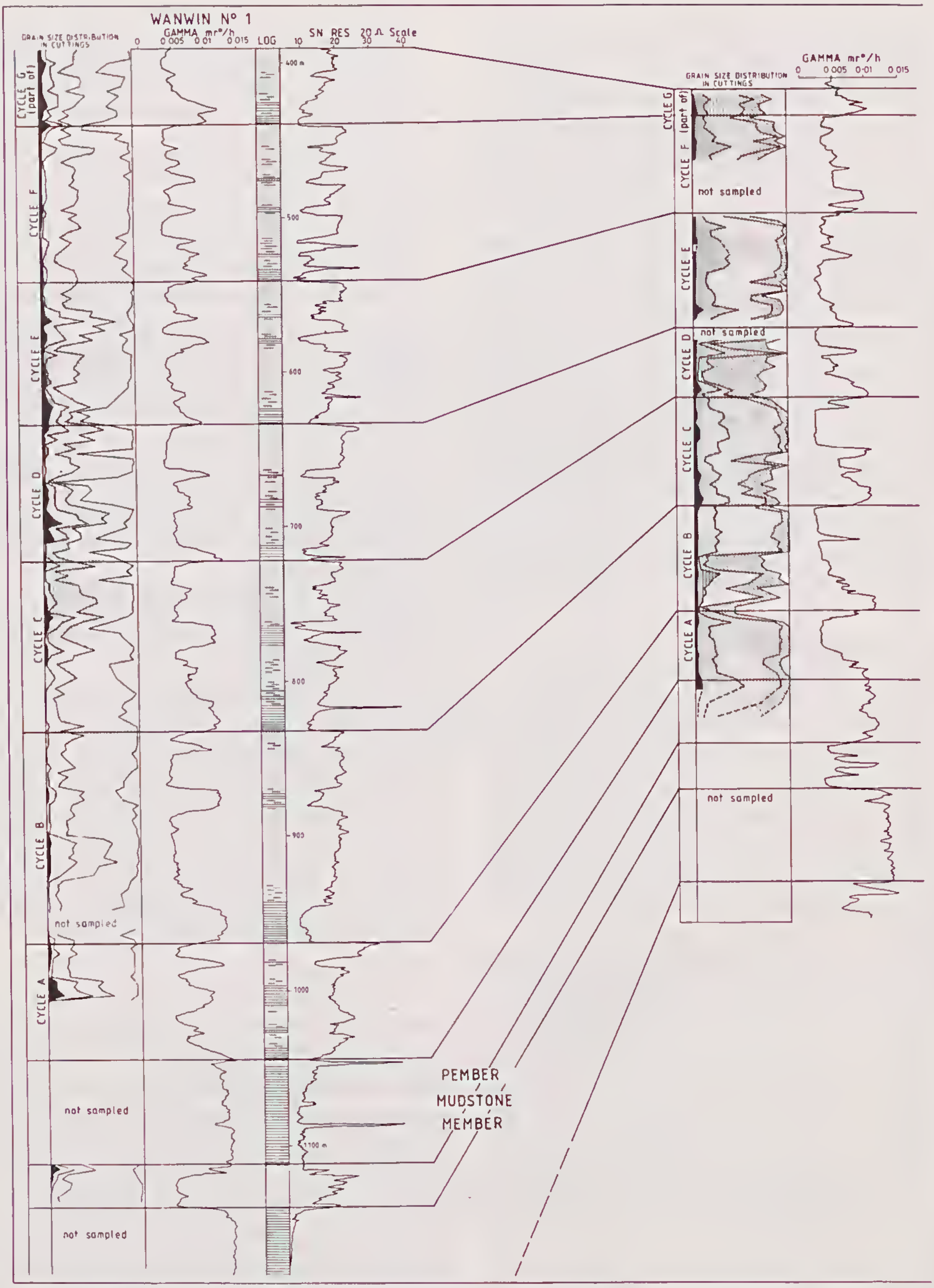


Fig. 7—Reduced wireline logs and grain size distribution of Dilwyn Formation sands in 3 Bores—Gambier Embayment (Victoria) Otway Basin.

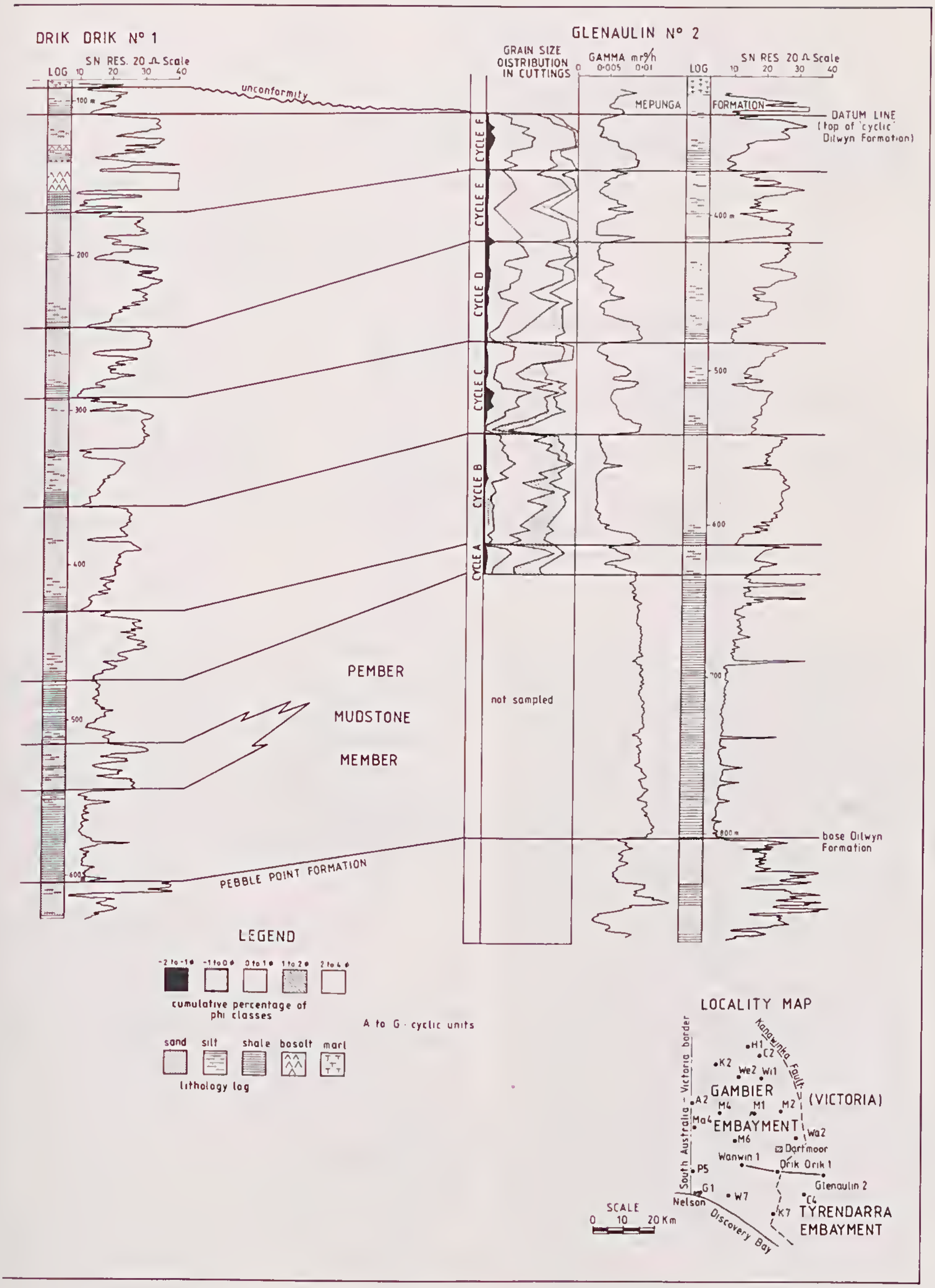


Fig. 7 (Continued)

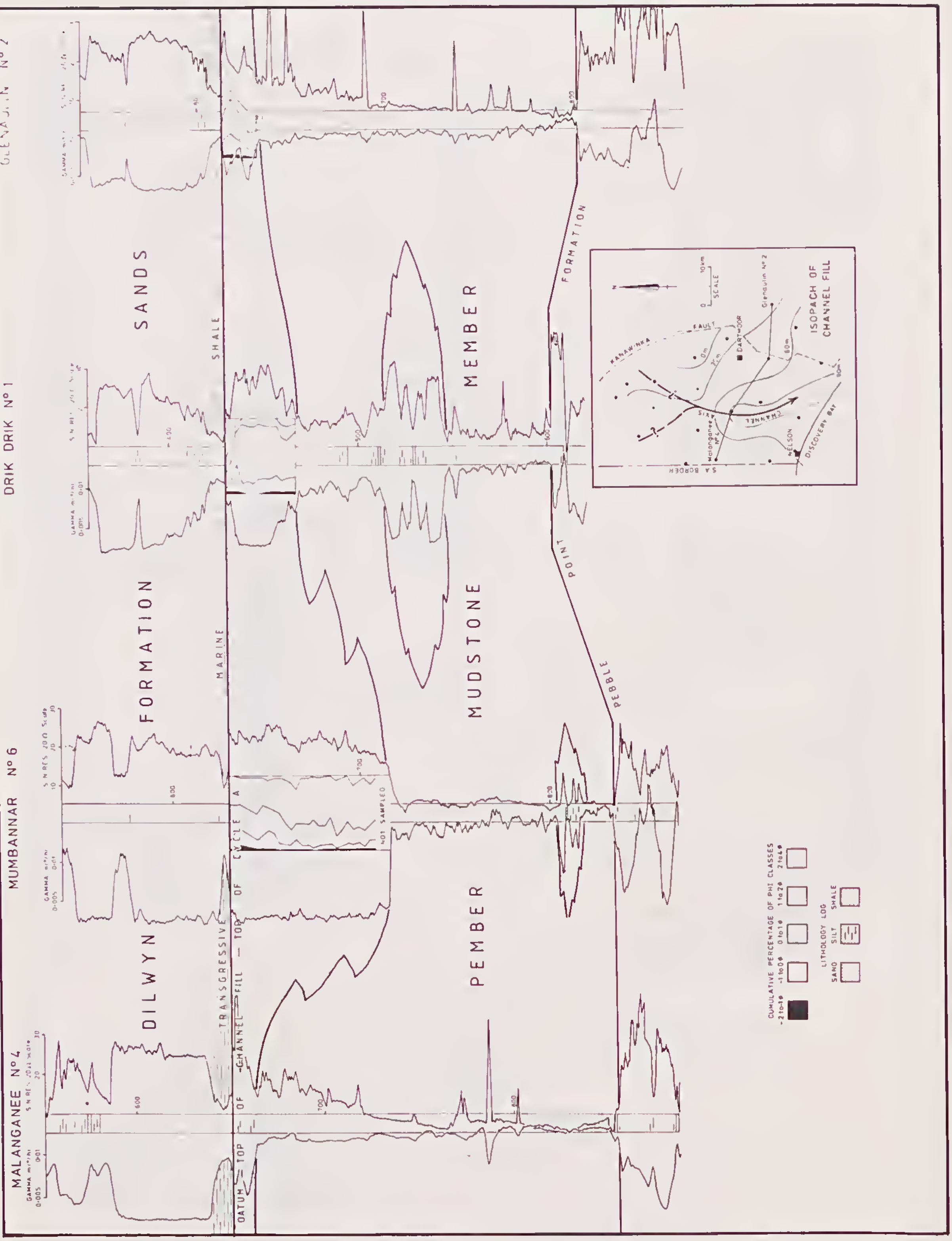


Fig. 8—Stratigraphic cross-section and grain size distribution of the Mumbannar Channel.

TABLE 1
DIPMETER RESULTS

Bore Name and Sand Unit	Red Patterns	Blue Patterns	Relationship between Dip Direction and Main Trends of the Sand Isopachs (Figs 14-19)	Wire-line Log Profile of Sand Body
Voluta No 1 Pember Mudstone Sand	4°-15°@350°N 3°-13°@ 40°N	9°-13°@40°N	At right angles	Coarsening upward
Voluta No 1 Cycle A—Sand Body	2°-10°@220°S 3°- 8°@165°S	4°-17°@165°S	Parallel	Box-like
Caroline No 1 Cycle B—Lower Sand	— —	5°- 7°@105°E 2°- 5°@140°E	Parallel? (axis not clear in this area)	Box-like
Caroline No 1 Cycle B—Upper Sand	—	8°@235°	Parallel?	Box-like
Caroline No 1 Cycle C Lower Sand	9°@05°N	8°- 9°@ 05°N	Diagonal to right angles	Coarsening Upward
Caroline No 1 Cycle C—Upper Sand	2°- 6°@320°N	2°-15°@180°S	Right angles for red patterns, parallel? for blue patterns	Box-like

seaward side. In the study area only two bores have three-arm dipmeter surveys run through parts of the Dilwyn Formation. These are the oil wells of Caroline No 1 and Voluta No 1 (Fig. 2). All dips are recalculated after subtracting the structural dip as determined by the methods given by Schlumberger (1970) and the results are tabulated in Table 1. The results generally indicate that dip directions parallel the depositional axis for box-shaped sand bodies, whereas for coarsening upward sand bodies major dip directions occur at right angles and dip towards the depocentres.

DISCUSSION AND CONCLUSIONS

DEPOSITIONAL ENVIRONMENTS IN THE DILWYN FORMATION

The Pember Mudstone represents a prodelta sequence of marine shales and silty shales which grades upwards into delta front facies. These sediments partially filled a deep east-west trending trough in the central part of the Otway Basin between the Gambier and Tyrendarra Embayments. Sands within the Pember Mudstone are characterised by coarsening upwards log profiles, excellent sorting coefficients, and linear geometries parallel to the main Portland Trough margins, and hence probably represent palaeoshorelines which formed periodically with marine regressions during this depositional phase. Cross bedding dips to the north, normal to the shoreline trends may indicate the sediments were derived from the seaward side.

The cyclic sequences which typify the undifferentiated Dilwyn Formation consist of two genetically different units, subdivision of which is based on geometry and facies equivalents. The first genetic unit, Cycle A, represents the delta front and delta plain equivalents to the upper part of the Pember Mudstone—the two thus forming a single large deltaic sequence. This cycle comprises thick channel and stacked channel sands which form two large lobate deltas similar to the Mississippi birdsfoot deltas (Fisk *et al.* 1954). These are named the Mumbannar Channel and the Portland Channel for convenience. The channels prograded southwards from two distinct fluvial sources which followed down the north-south trending re-entrants at each end of the Portland Trough, and cut at right angles across the main basin trends. The channel sands eroded into and prograded over the delta front silts and shales of the Pember Mudstone. Their lateral facies equivalents between the delta lobes comprise sparsely fossiliferous laminated and cross bedded silty shales and silts interspersed by carbonate cemented sands, and represent deposition under more brackish water conditions in interdistributary bays.

A marine transgression over these birdsfoot deltas represented by the fossiliferous shales at the base of Cycle B marks the end of this Mississippi-type high constructive delta phase, and the beginning of a series of stacked tidal dominated delta cycles B to G. This second genetic sequence of strata resembles more closely the Niger Delta examples (Weber 1971) and consists of up to six high sand to shale ratio cycles, without large seaward prodelta components. The single major depocentre for each cycle is broadly coincident with the boundaries of the Portland Trough, and with each successive cycle this preferred lineation becomes more apparent (Figs 10-13).

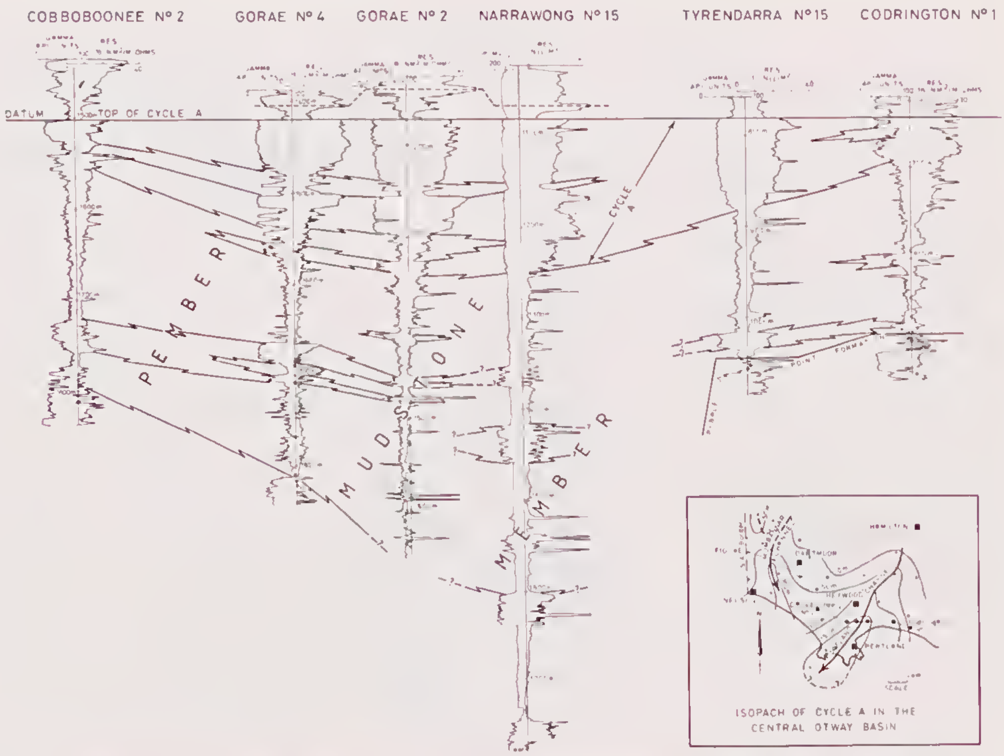


Fig. 9 — Wireline log cross-section across the Tyrendarra Embayment of the Otway Basin, below the top of Cycle A.

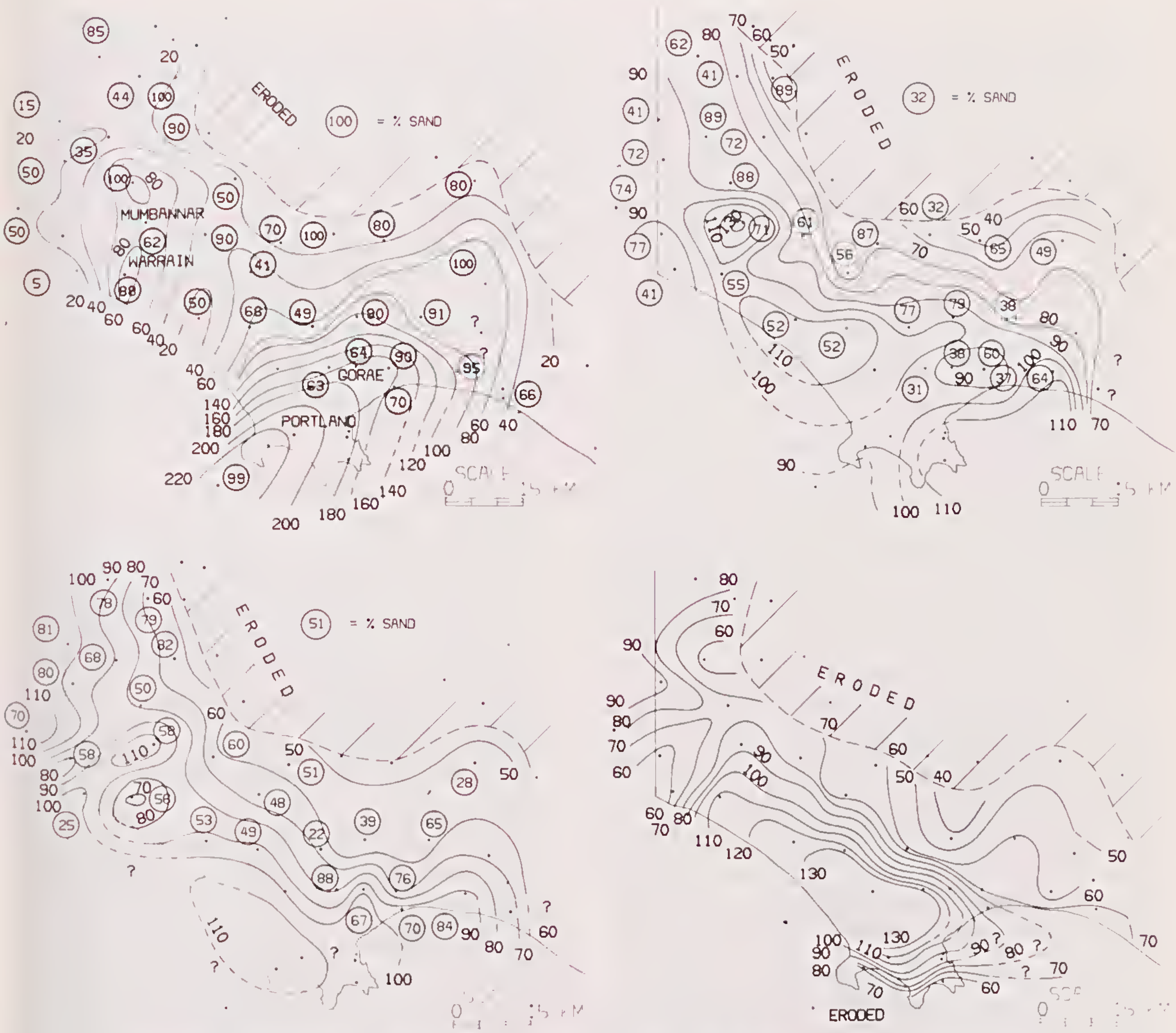
However, when the individual sand bodies which make up each delta cycle are examined, it is apparent they have multi-environmental origins.

The lower sand in Cycle B shows box-like log profiles occurring in a south-west trending depocentre through the Mumbannar-Caroline areas, indicating a westerly shift occurred to the Mumbannar channel axis of Cycle A. This large distributary channel prograded seawards through a barrier bar sequence typified by the coarsening upwards log profiles in bores which lay along the northern edge of the Portland Trough in the Glenaulin, Heywood and Narrawong areas. The lack of any similar large channel-like developments in the Gorae area indicates a diversion of the previous Cycle A Portland Channels, possibly into the Mumbannar area. Dipmeter data in Caroline 1 indicate some contradicting evidence for channel flow directions, with blue pattern dips trending south-east normal to the channel sides. This may be explained by the multi-environmental origin for this sand body, which includes some parts derived as channel deposits and others from barrier bar deposits. On the seaward side of the combined channel-barrier system there are up to 30 m thick shales which probably thicken offshore as the sands thin.

After a thin shale interval the re-establishment of the Cycle A channel directions took place. The V-shaped depocentre of the upper Cycle B sand comprises box-shaped log profiles in the western arm, suggesting mainly a fluvio-deltaic environment. Blue pattern dip directions indicate channel flows to the south in the Caroline 1 area approximately parallel to the depocentre axis. Mixed box-like and coarsening upwards profiles in the eastern arm suggest some barrier sand intervals. The sharp upper contact with the overlying marine shales is associated with carbonate cemented sands in inter-distributary areas, and marks the end of the Cycle B delta phase.

The lower shales of Cycle C progressively coarsen upwards into a long linear sand body typical of delta front barrier sands. Parallel red and blue pattern dip directions to the north normal to the depositional axis suggest this barrier complex was similar to barrier sands in the Pember Mudstone, with sediments being derived primarily from offshore. The sands thin to the north probably grading into back barrier lagoonal shales, and offshore to the south into marine shales. This barrier complex is overlain by shales of probable delta front facies.

The upper sands of Cycle C show maximum development accompanied by box-like profiles at the western end of the study area. The lack of bores in the South Australian section means further environmental interpretation is difficult, although all indications suggest a re-established Mumbannar type fluvio-deltaic channel sequence flowing SSW. Blue pattern dips in Caroline 1 located near the depocentre of the channel also trend SSW. An area of no sand development in the Heywood area may represent a local unconformity or non-



Figs 10-13—Central Otway Basin isopachs (metres) of Cycles A (10), B (11), C (12), D (13). Encircled numbers are sand percentages. Numbered left to right on top then beneath.

deposition area separating the westerly channels from further channels developing in the south-east.

Cycles D to G follow similar patterns of sedimentation. Some basalts are intercalated at various levels in these cycles such as Drik Drik 1, Homerton 3, and Codrington 1. These are probably sills as the basalt date of 37 million years on the Codrington 1 basalt (Bowen 1974) is considerably younger than the palynological age of equivalent sequences elsewhere. Thicker basalts at the top of the Dilwyn Formation in the Cobboboonee 2, Heywood 10 and 13 bores are also probably sills (Abele *et al.* 1976).

The deltaic sequences ended in the Middle Eocene when a marine transgression deposited silts and shales of the Burrungule Member across the Portland Trough. Marine transgression over the area was complete by the Late Eocene. Fluvio-deltaic sequences were not re-established during or subsequent to this transgression phase.

Rates and Sources of Sedimentation

The large volumes of sediment comprising the Dilwyn Formation must have been deposited rapidly from at least two northerly sources in the vicinity of the present Western Highlands. In the centre of the Portland Trough minimum sedimentation rates for the Pember Mudstone and undifferentiated Dilwyn Formation are approximately 0.3 m/1000 yrs over a period of 4.5 million years, assuming an upper age limit at the Middle-Late Eocene boundary. Actual sedimentation rates were probably much higher considering that diastems occur at the end of each cycle, and subsequent post depositional consolidation has occurred.

The major depocentre of the Dilwyn Formation occurs in the Portland Trough which contains about 1000 km^3 of sediment covering some 2400km^2. By comparison to present day deltaic depocentres, this is similar in area to deltas of the Brazos (Colorado), Danube or Rhone Rivers, which discharge up to 100 million tonnes of sediment per year (Smith 1966). The sizes and geometry of the sand bodies in the Dilwyn Formation are equal to and in many cases exceed the dimensions of those described for the Niger Delta (Weber 1971) which has an annual sediment discharge of 25 million tonnes. This may be owing to the Dilwyn sands being derived from only two major point sources, whereas the Niger Delta sands occur at the mouths of a multitude of smaller delta distributaries.

The lack of any major rivers of comparative size and discharge rates in this part of Victoria today presents some difficulties for the reconstruction of palaeodrainage patterns. Either the dividing range in Eocene times was higher and experienced greater precipitation and erosion to sustain large rivers with short lengths; or else the deltas of the Portland Trough were supplied from rivers with larger watersheds coming through from the Murray Basin north of the divide.

The existence of a substantially higher dividing range in the Eocene has been refuted in the Eastern Highlands by the valley filling Tertiary basalts and their ages obtained by Wellman (1974) who infers that the dividing range has maintained its heights and extent to the present. Climatically the Lower Eocene in southern Australia is considered to have experienced greater precipitation (e.g. Harris 1965, Gill 1975, Martin 1977, Kemp 1978), but for the lower lying Western Highlands is unlikely to have produced substantial river deltas unless accompanied by topographically higher and/or greater areas of watershed.

Major rivers may have come from north of the divide into this part of the Otway Basin during Eocene and pre-Eocene times (Denham & Brown 1976, Gostin & Jenkins 1980, Harris *et al.* 1980). Supportive evidence from this study includes:

1 – The major re-entrant at the eastern end of the Portland Trough trends northwards towards the present low saddle in the dividing range between the Grampians to the east and the Dundas Tablelands to the west. The re-entrant at the western end of the Portland Trough trends northwesterly towards the low basement saddle of the Padthaway Ridge which divides the Otway from the Murray Basins in South Australia.

2. The cessation of deltaic sedimentation near the end of the Early Eocene coincides with folding and uplift north of the Tartwaup Fault, as indicated by the unconformity on top of the Dilwyn Formation and the suggested time break (McGowran 1978). Marine transgressions subsequently occurred from the south. This uplift could have blocked the Murray Basin river sources along the divide. The Murray rivers then became confined to the Murray Basin, and without this major sediment source open marine transgressions in the Middle Eocene could begin from the south (the Burrungule Member). It, therefore, seems likely that the postulated Early Tertiary outfall for the Murray River in the Spencer Gulf (Williams & Goode 1978) could have occurred subsequent to this Middle Eocene rise of the Eastern Highlands. This date would accord with the oldest (Late Eocene) dated channel sediments near the Mt Lofty-Flinders Block west of Morgan (Goode & Williams 1980). By Oligocene times there was negligible clastic input into the Otway Basin and marine carbonate shelf sediments (Heytesbury Group) spread right across the basin reaching practically to the edge of the divide. Failure of the river systems to re-establish their large deltas subsequent to the Late Miocene marine regression indicate that the Eocene sediment regime was reliant upon a large sediment supply such as from north of the divide and was not repeated.

Eustacy and Cyclic Sedimentation

The cyclical sedimentation may be attributed to two types of related causes:

i, those from outside the local area, e.g. tectonic changes, or world wide eustatic sea level changes;

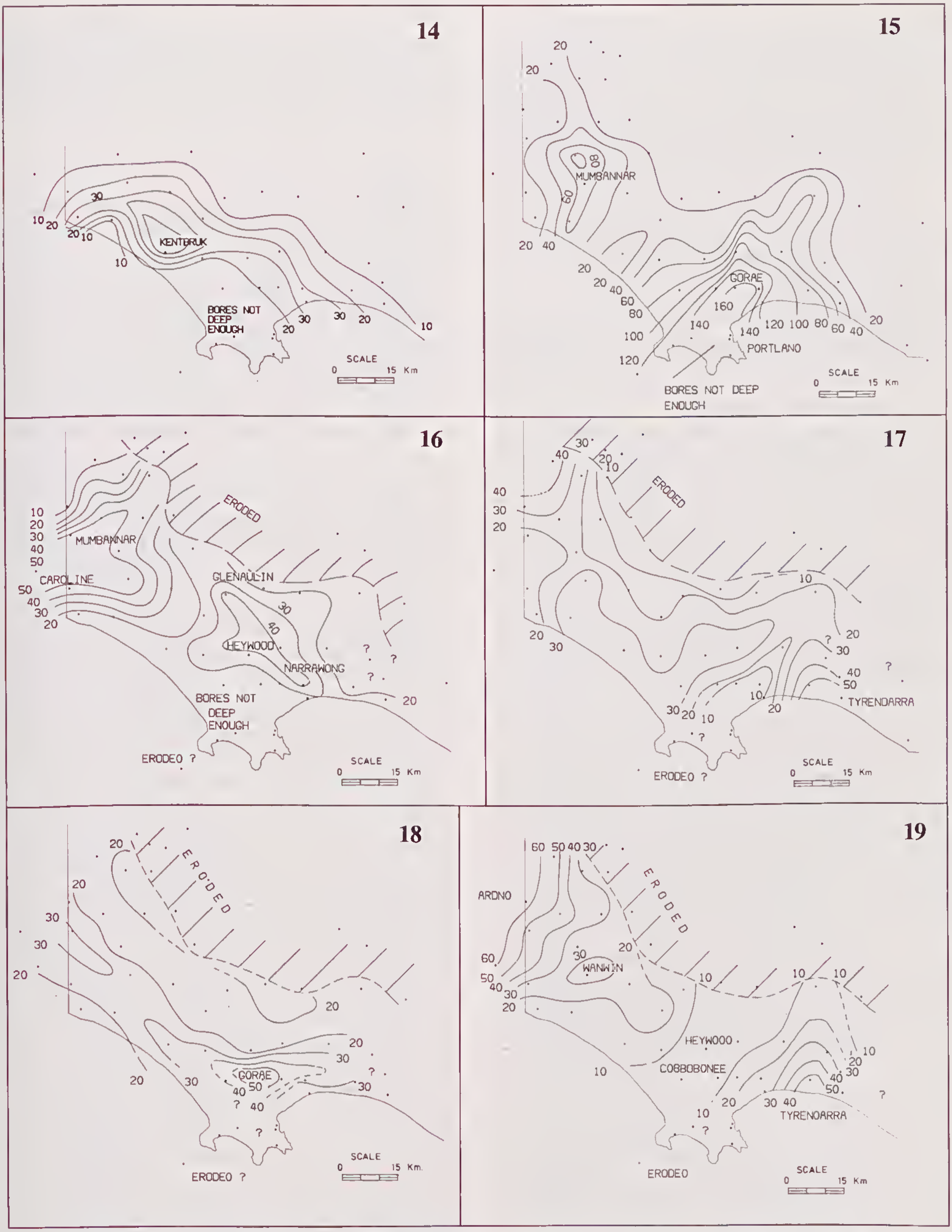
ii, those entirely within the local environment, e.g. delta cycles produced by the shifting and abandonment of successive delta lobes.

The relative contribution each one makes to any given sequence of strata is subject to individual interpretation. In the Otway Basin cyclic sedimentation is considered in terms of time, stratigraphic thickness and area distribution.

The primary cycles consist of four main transgressive-regressive events (Bock & Glenie 1965), which relate to tectonics and eustacy and their interactions with basin development (Glenie *et al.* 1968). The Dilwyn Formation is described by them as one major coarsening upward-decreasing marine influenced regressive cycle, commencing with a rapid transgressive phase at the base (Pebble Point Formation, and Pember Mudstone Member), grading up into a slow regressive phase (undifferentiated Dilwyn Formation and Dartmoor Sand Member). The Burrungule Member was not recognised at this time and the Mepunga Formation became the base of a new cycle of marine transgression.

Second order cycles were referred to by Bock & Glenie (1965) as subcycles, but were not elaborated upon. The time span and stratigraphic thickness of second order cycles are probably more closely analogous to the eustatic cycles identified in the Gippsland Basin (Partridge 1976). As these eustatic cycles are best defined from good quality seismic and palynological data they are not so easily identified in the study area. By inference some of the major intra-Dilwyn Formation events may relate to contemporaneous eustatic events in the Gippsland Basin as suggested by Partridge (1976), but remain to be better defined.

Third order cycles are those created by local changes in depositional environment. These are the fundamental



Figures 14-19—Central Otway Basin isopachs (metres) of Pember sand (14), Cycle A sand (15), Cycle B lower sand (16), Cycle B upper sand (17), Cycle C lower sand (18), Cycle C upper sand (19).

factors which contribute to the cyclic sedimentary sequences in the Dilwyn Formation. Each cycle commences with a rapid marine transgression across the area followed by slower regression which accompanied the differential filling by clastic sediments of the newly created basin. These transgressive events are interpreted to have been similar to those occurring in modern lobate deltas such as the Mississippi Delta (Fisk *et al.* 1954). In the Mississippi case a series of overlapping delta lobes were created by the shifting of distribution channels into new areas during Pleistocene to Recent times. Once abandoned, each delta lobe continued to subside and hence underwent subsequent partial destruction during renewed marine transgression.

Reworking of the topmost sand in each Dilwyn cycle accompanies the seven transgressive phases, as identified by the sharp upper contacts associated with carbonate cemented sands. This contact signals the start of a new cycle by abandonment of sediment supply. The earliest transgressive phase was the deepest and most stable and was accompanied by the deposition of more than 100 m of prodelta shales (the Pember Mudstone) in inter-distributary areas, and more than 600 m of sands and shales at the lobate delta mouths of the main distributaries (Cycle A and Pember Mudstone). In this cycle the rate of deposition would necessarily exceed the rate of subsidence (Curtis 1970).

A major intra-formational event at the end of Cycle A occurred and altered the depositional pattern from one of thick lobate high constructive deltas to one of thinner, individually more linear and parallel to the palaeoshorelines, stacked delta cycles with characteristics similar to tidal dominated deltas. It is tempting to associate this change with one of the Gippsland Basin's eustatic events within the *M. diversus* Zone, but equally its causes may be related to fundamental changes in the local distribution patterns. Each cycle averages about 80 m in thickness (which may tentatively indicate approximate water depths by the methods outlined by Klien 1974), even though the component lithologic units show marked lateral thickness variations. By comparison with examples given by Curtis (1970) this is more likely to indicate a widespread and uniform subsidence rate with an equal rate of sediment supply. The relative influence of the marine environment does not appear to decrease from one cycle to the next, rather grain size analyses show that each cycle is a replica of the one below. This appears to contradict the overall first order cycle scheme of Bock & Glenie (1965) which predicts a decrease upwards in marine influence concurrent with an increase in grain size. In fact, at no time was the Portland Trough remote from marine influence. Areas peripheral to the trough became ones of non-deposition and erosion as subsidence continued without an adequate sediment supply, so that when marine transgression did occur throughout the basin in the Late Eocene a major unconformity had been formed.

Hence in the study area, and also probably throughout the Otway Basin, the depositional cycles of the Dilwyn Formation can be considered more in terms of the depositional processes acting within, rather than the vertical and lateral facies changes being a consequence of any basin wide tectonic or eustatic cycle. By analogy the underlying Late Cretaceous Sherbrook Group which comprises a similar clastic sequence could also be considered in these terms.

Offshore Trends

Despite the lack of adequate well control offshore (1 only), the following trends are considered likely to occur:

The Portland Trough is open to the southeast and probably extends some distance offshore into Portland Bay. In doing so it may close against the offshore extension of the Warrnambool Ridge, or it may cross the front of this ridge to connect with a secondary Tertiary depocentre off the Port Campbell Embayment (Fig. 1).

North to south bore hole cross sections (Wopfner *et al.* 1971, Abele *et al.* 1976) and seismic interpretations (e.g. Robertson *et al.* 1978) indicate that the Wangerrip Group thins out beneath the middle and outer continental shelf areas. Offshore wells in the Port Campbell Embayment and South Australian part of the Gambier Embayment indicate this to be the case. In most instances deltas are observed to thin offshore in a similar manner.

It can be anticipated from the delta model that in the offshore areas the Dilwyn Formation would become increasingly shaly to the detriment of sands. The only offshore well in the study area (Voluta 1) was sited along the line of the major distributary channel of the Pember Mudstone and encountered a sand section over 250 m thick, indicating this lobate delta extended seawards of the present shoreline by up to 7 km. Similar thick sand sequences occur in the closest DMEV bores at Portland and near Cape Bridgewater. From palynological results (Ripper 1976) and lithostratigraphic correlation (this paper) none of these DMEV bores reached the base of the Tertiary as previously suggested by Glenie and Reed (1961) and Leslie (1966). This is due to the substantial thickening in the overlying Heytesbury Group, and the depth limits of the DMEV drilling rigs. The full Dilwyn sequence has not been penetrated in this area. Criteria for recognition of the Pebble Point Formation have been discussed by Holdgate (1977c). Similar lithologies have not been observed in any of the Portland bores, but are present in the sidewall cores in Voluta 1 at 1300 m and 1320 m.

The suspected lack of delta cycles B through G in Voluta 1 indicates either they did not prograde this far offshore, or else were removed by subsequent erosion prior to deposition of the Late Eocene Mepunga Formation. The closing of the isopach contours on Fig. 3 suggests considerable thinning of the total Dilwyn Formation offshore in Discovery Bay. No Middle Eocene (Burrungule Member) sediments are present in Voluta 1 suggesting that it is on a structurally high position relative to the Portland Trough similar to areas north of the Tartwaup Fault. This fact would suggest some erosion of the topmost Dilwyn beds has occurred between the Lower and Upper Eocene.

Deep water canyons (Bridgewater canyons), and buried canyons on the continental slope 36 km southwest of Cape Bridgewater (Fig. 1) have been discussed by Hopkins (1966) and Von der Borch (1968). Both authors assign a later Tertiary age for the canyons. It appears more than coincidental that as river cut features in an area where substantial rivers onshore are lacking, they should occur on line to the major Early Eocene channels of the Dilwyn Formation. This age is similar to that assigned to other canyon cutting episodes in southern Australia (Von der Borch 1968). It, therefore, could be argued that while the present canyon sediment fill has a Late Tertiary age they reflect deeper subsurface early Tertiary cutting events when larger rivers occurred in this area, and when a marked shelf break may not have existed. In this way they are similar to the association of past and present canyons on the continental slopes off the Gippsland Basin.

Hydrocarbon Prospects

In Otway Basin summaries (Wopfner *et al.* 1971, Robertson *et al.* 1978) the Dilwyn Formation is considered to be less attractive as a hydrocarbon prospect than the underlying Cretaceous sediments, due mainly to fresh water flushing and the lack of sufficient overburden.

The Portland Trough has not been drilled for oil, and its definition has only recently been established by DMEV drilling. For the following reasons this trough may hold more promise:

1. The Dilwyn Formation is thicker here, and buried deeper than other parts of the basin. If trends continue, the offshore extensions to the trough should see the lower part of the Pember Mudstone reach burial depths over 2000 m, giving a better chance to find these sediments at sufficient maturity.
2. The Tertiary sediment pile in the trough is thick, and was deposited more rapidly than in surrounding areas of the basin. In the Dilwyn Formation the sediments were deposited in a deltaic environment. These factors are considered to have an important bearing on the hydrocarbon producing areas in the offshore Gippsland Basin (Kantsler *et al.* 1978).
3. As a source rock the thick shales of the Pember Mudstone contain abundant coaly organic matter. Some vitrinite reflectance values (Ro max %) in the centre of the onshore trough are up to 0.56% at 1560.9 m (A. J. Kantsler pers. comm.). Deeper burial offshore could see these values increased to bring the sediments into the oil window at 0.60%.
4. The sands of the Pember Mudstone have porosities of 28% or above (Laing in Holdgate 1977a), and include beach and offshore bar environments. They occur as lenses and linear bodies which in the more distal regions of the trough away from the main distributary centres are likely to be isolated from major fresh water flushing paths. They are also likely candidates for porosity pinchouts.
5. None of the deeper Tertiary sands in the Portland Trough have been tested, although shows of hydrocarbons on gas detectors and encouraging wire line log interpretations have been made (Laing in Holdgate 1977a). The upper beds of the Sherbrook Group and the Pebble Point Formation also contain some potential as provided by the shale seals of the Pember Mudstone and the unconformable relationship between the Upper Cretaceous and Tertiary sediments.

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